Sustainable Design of Energy Systems – The Case of Geothermal Energy

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Abstract

Geothermal energy is one of the renewable energy resources with a vast potential in many areas around the world. It has a strong spatial dimension and its utilization for electricity and heat production requires an integrated development framework. In this work we present a design framework for sustainable geothermal systems incorporating modules covering the various aspects of exploration, utilisation, end-use and management.

The overall framework consists of a number of models: a geophysical model for the assessment of the geothermal reservoir capacity, a management model (geothermal wells, pumping and re-injection), a distribution network model, an end-use model, and an environmental model for sustainable operation. It incorporates the basic axes of sustainable development, i.e. resources, economy, environment, energy, technology, society. Subsequently it is applied to an existing geothermal reservoir in Lesvos, Greece, which at the present is underutilized, from an energy, environmental and economic perspective. The search for an optimum design includes the formulation of different scenarios and the multi-criteria decision analysis.

Key words: Energy Systems, Sustainable Design, Geothermal Energy, Decision Analysis

1. Introduction

It is well known that sustainability could be enhanced by increasing the share of Renewable Energy Sources (RES) in the energy system. Moreover, RES improve the security of energy supply by reducing dependence on imported energy. In the EU, for example, the energy dependence on energy imports is already 50% and is expected to rise up to 70% by 2020 if no action is taken (European Commission, 1997). Furthermore, the EU has committed to an 8% reduction of greenhouse gases for the period 2008 to 2012, compared to 1990, as part of the Kyoto Protocol. Endorsement of RES is acknowledged as a substantial step towards achieving these targets.

Planning for optimality of a sustainable energy system must incorporate the modelling of a large number of design variables and alternatives. The design of such a system should be the output of an integrated model where all constraints and relevant attributes are accounted for. It is the purpose of the following sections to outline the structure of such a framework for sustainable design of geothermal energy projects.

In this paper, the geophysical, resource-based, technological, economic, environmental and social characteristics of low-temperature geothermal systems are incorporated in such an integrated model. The various features and interactions which characterize such systems are then incorporated within a design methodology based on multi-criteria decision analysis that promotes overall sustainable project design. Subsequently a case study in the island of Lesvos, Greece, is employed to illustrate the various facets of the sub-modules. The approach emphasizes the local dimension of such systems and the interface between their particular layout and the structure of the rural/urban areas they are designed to serve. These areas are characterised by small heating periods, e.g. October to April, and low thermal density requirements.

2. Geothermal Energy

Geothermal energy is the energy contained in the heated rock and fluid within the earth's crust. It is considered a renewable energy source since a geothermal resource may be prolonged by reinjecting the waste fluid, back to the original reservoir. Thus geothermal resources can be considered renewable on the time-scales of human technological/societal systems and do not require the geological times of regeneration of fossil fuel reserves.

Geothermal resources are suitable for many different types of uses but are commonly divided into two categories, high- and low-enthalpy according to their energy content. High-enthalpy resources (>150 °C) are suitable for electricity generation within conventional power cycles, whereas low-enthalpy resources (<150 °C) are employed for direct heat uses and electricity generation using a binary fluids cycle.

Geothermal energy has been produced commercially on the scale of hundreds of MW for over three decades both for electricity generation and direct utilisation in many parts of the world. It has a number of positive features which make it competitive with conventional energy and some renewable sources. These features include:

- it is a local energy source that can reduce demand for imported fossil fuels,

- it has a positive impact on the atmospheric environment by displacing combustion of fossil fuels,
- it is economic competitive with conventional sources of energy,
- geothermal plants can operate continuously, without constraints imposed by weather conditions, unlike other renewable sources,
- it has an inherent storage capability and is best suited to base-load demand,
- it is a reliable and safe energy source which does not require extreme storage or transportation of fuels.

In year 2000, the geothermal electrical installed capacity in the world was 7974 MW, and the electrical energy generated was 49.3 billion kWh, representing 0.3 % of the world total electrical energy (5,342 billion kWh in 2000) (Barbier, 2002). The thermal capacity in non-electrical uses (greenhouses, aquaculture, district space heating, and industrial processes) was 9000 MWt (year 1998) (Lund, 1998).

One of the most efficient direct uses of geothermal energy is district energy, in which the hot fluids are distributed through a pipeline network to multiple users.

3. The outline of the integrated model

The sustainable design of energy systems includes the integration of technological, resource base, economic, environmental and social parameters. The basic structure of such a framework for geothermal energy is illustrated in Figure 1. The *Technological* model consists of the Geothermal Reservoir and the Heat Transport; the *End-Use* model incorporates all possible applications; the *Environmental* model assesses an overall life-cycle analysis and a local environmental impact assessment; the *Economic* model deals with the economic sustainability of the project. Finally the *Decision Analysis* model deals with the overall management of the project, the implementation of a decision-making process that assures local justification and the social impact assessment. The various state variables and parameters that compose the geothermal sustainable design framework are outlined in Figure 2, while the rest of this section discusses some significant properties of these models.

3.1. The *Technological* model

A schematic of a typical system for the utilization of a low-enthalpy geothermal field in a direct-use system is presented in Figure 3. The various aspects of the technological model are:

- Geophysical
- Drilling
- Pumping and Heat Exchanging
- Transporting
- Storage
- Control and Monitoring
- Distribution
- End-Use
- Reinjection

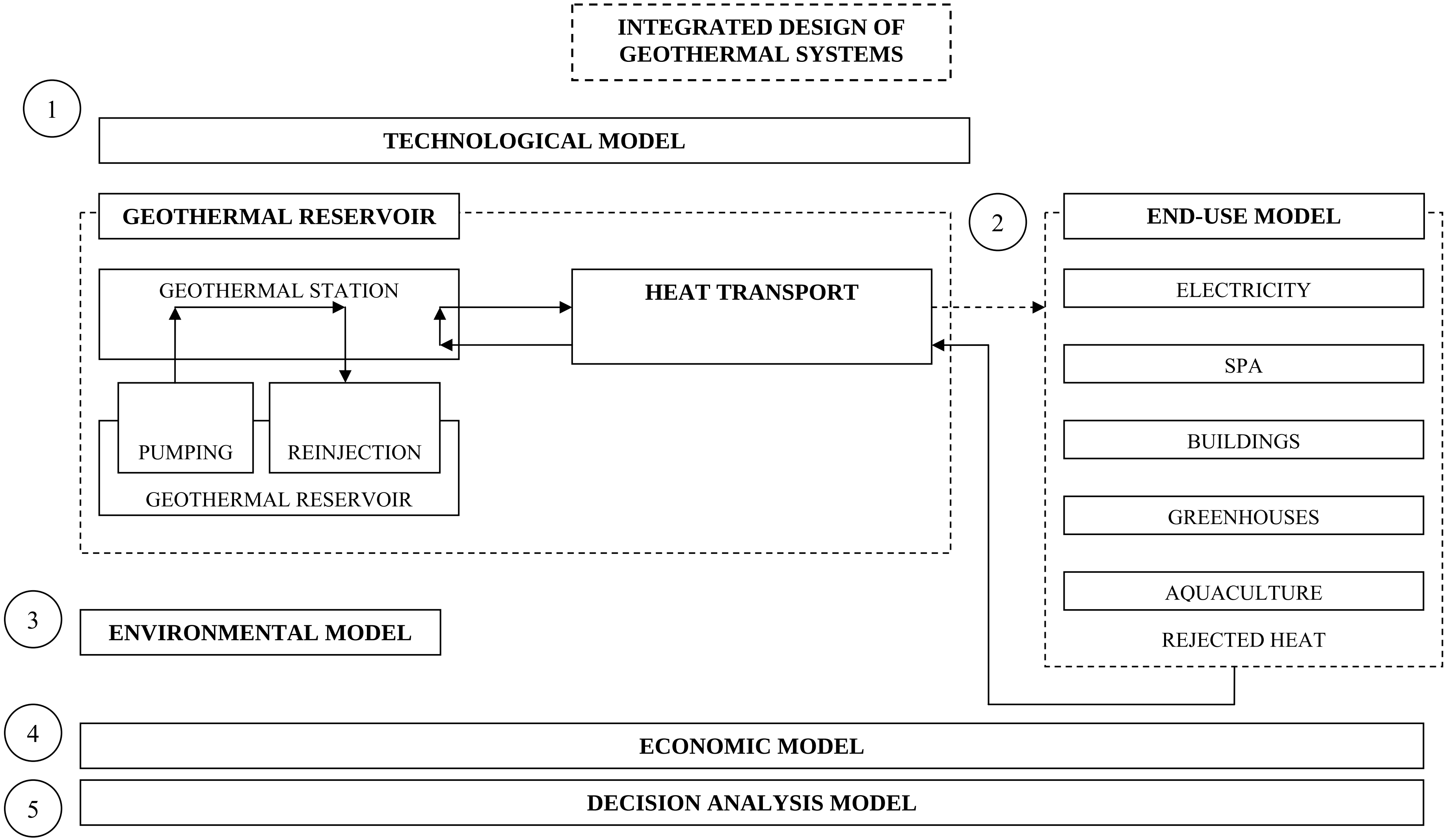

Fig.1. Integrated Design of Geothermal Energy Systems

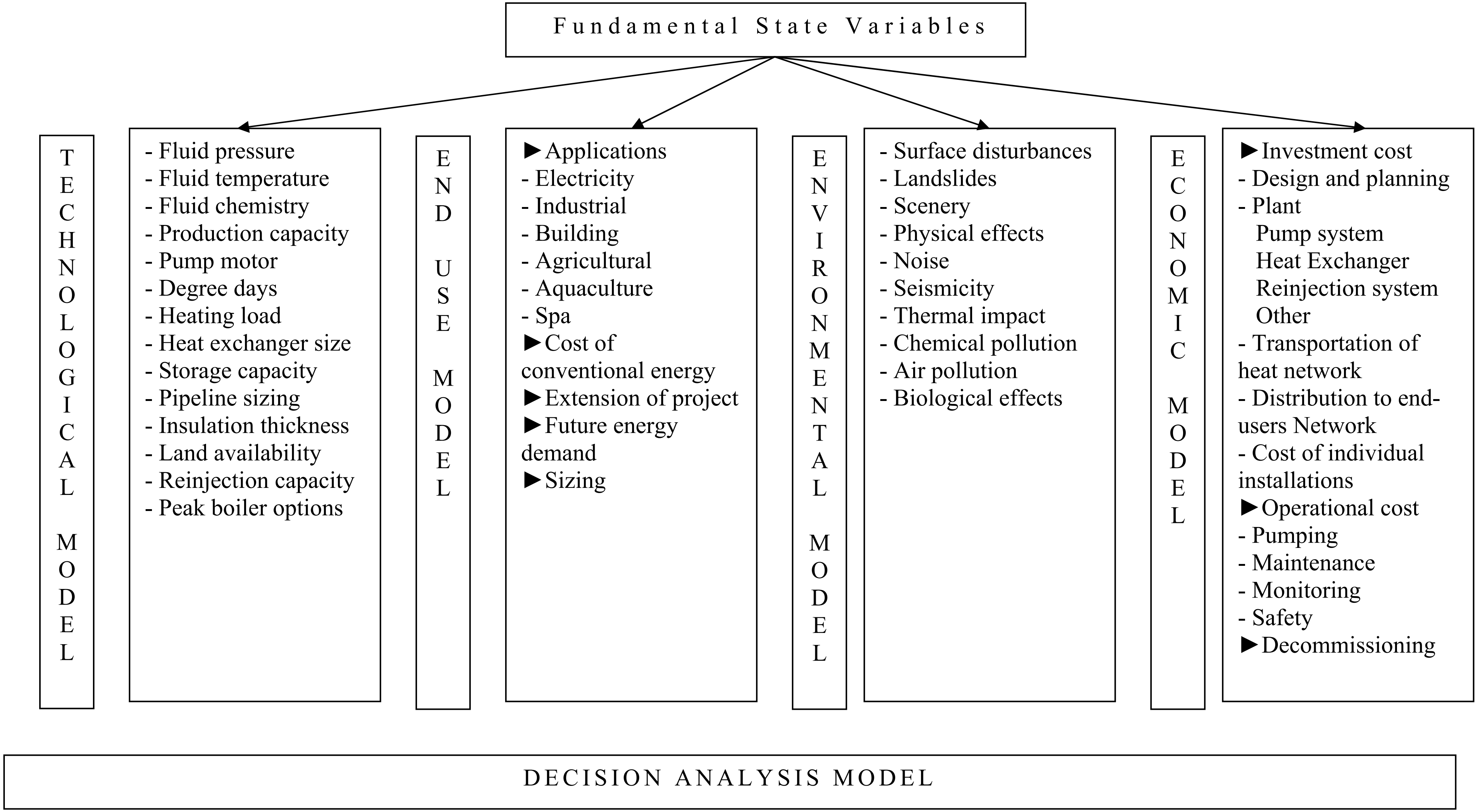

Fig. 2. Overall Sustainable Design Framework; Fundamental State Variables

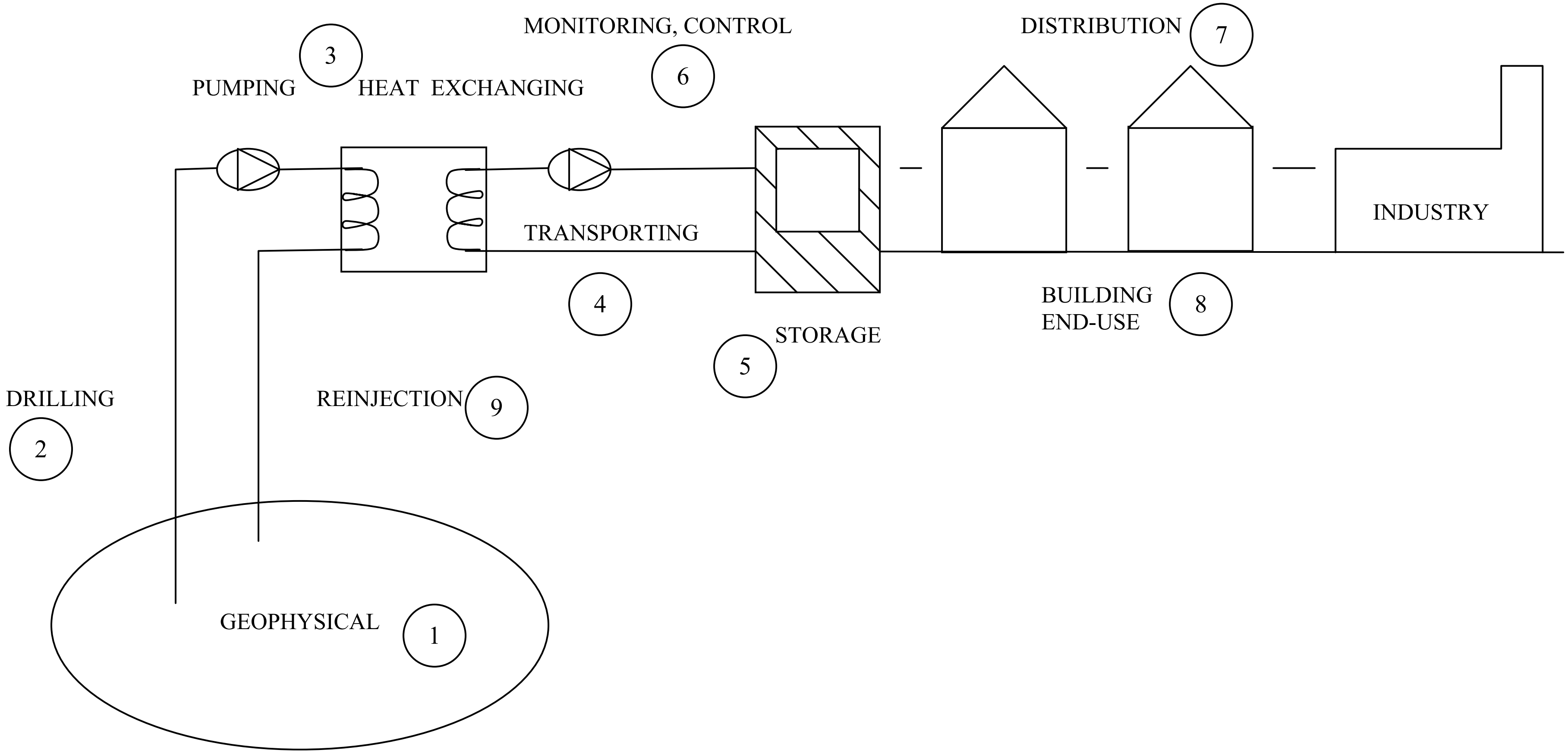

Fig. 3. The Geothermal Technological module

The Geophysical module includes the assessment of the geometric (spatial, depth, thickness), hydrodynamic (natural flow, static pressure, dynamic viscosity of the water), thermal (temperature of the water, thermal conductivity, calorific capacities of the rocks and water), and chemical (salt content, etc.) characteristics of the resource. Data on these factors are necessary in order to estimate the available energy and future productivity and to assess the performance of the aquifer under different exploitation schemes. The geothermal resource must be carefully assessed but often is not fully known until it is utilised over a sustained period of time.

Drilling represents the first step in the process of extracting hot water from the geothermal reservoir and the last step of reinjecting disposal fluids back to the geothermal pool. The sitting of the extraction and re-injection wells may become an important design variable since it determines the magnitude of the pressure and thermal interferences of the geothermal fluid. This drilling module could incorporate GIS mapping, exploratory drillings, and assessment of potential yield through production tests.

The Pumping and Heat Exchanging module aims to the optimal sizing of the mechanical equipment used, such as conventional pumps, heat exchangers, steam turbines and generators.

The Transportation module is a system of pipelines that transport hot water from the extraction wells to the points or zones of utilization. Various technical problems must be solved when designing such systems (Guidmann, Rosenthal, 1981).

The Storage module is an optional feature which may be necessary for the smoothing of the operation.

The Control and Monitoring module manages the function of the various sub-systems and attempts to optimize operation.

The Distribution module refers to the areas where the energy consumers are located. The cost of distributing the geothermal fluid is related to urban structure, house connections, residential and other land uses densities.

The End-Use module is considered as to be a discrete model, since it deals not only with the technological constraints of resource exploitation but also with the determination of the most appropriate scenarios for final uses including local social and institutional parameters.

The Reinjection module deals with fluid disposal of the return cooled waters into the same underground geothermal reservoir.

Due to its particular characteristics each geothermal projects needs an exact and careful analysis. This is the reason the spatial features of geothermal district heating systems are of vast importance since such systems are characterized by increased uncertainty about their feasibility when implemented in real places (Sommer et al, 2003). Particularly the exact location of the wells together with the position of the energy demand centres, determine the spatial extension of the transportation network, the length of which has a definite impact on heat and pressure losses and the economics of the project. The location of potential energy markets determine the characteristics of the Transportation module, while the internal structure of these markets, in terms of land-use mix and density, determines the characteristics of the Distribution module (street mains, house connections).

3.2. The *End-Use* Model

It deals with the final user application and it may include electricity, industrial applications, balneology, building heating, greenhouse heating and other agricultural uses, and aquaculture heating. Principally, cascading exploitation of geothermal resources is considered to be an advanced practice of exploitation where the resource is utilised in steps of ever-decreasing temperature: e.g. electricity production, industry, space heating, agricultural use, aquacultures (Rybach, 2003).

On the side of users, the design of the individual least-cost heating scheme involves the optimal determination of several variables such as the exchanger surface, the heat pump power, the back-up system capacity, the temperature of the residual geothermal fluid sent back to the distribution system, as well as various intermediate temperatures. The whole system has to be appropriately sized to provide the peak load, unless it is complemented by other energy sources such as a centralized fuel-fired peak boiler or back-up systems in each individual house.

3.3. The *Environmental* model

All energy production causes changes to the environment and requires some kind of engineering and building activity, which induces a number of environmental effects. Although geothermal energy is considered to be a clean and sustainable energy source, its development still has some impact on the environment and will lead to some emission of gases and effluents that require disposal.

Positive and adverse aspects of this environmental impact have to be considered prior to any decision to develop a geothermal field, as well as possible mitigation measures. The main environmental effects of geothermal development are related to surface disturbances, the physical effects of fluid withdrawal, heat effects and discharge of chemicals. More specifically, they could include (Kristmannsdottir, Armannsson, 2003):

- Surface disturbances
- Physical effects of fluid withdrawal
- Noise production
- Thermal impacts
- Chemical pollution
- Biological effects
- Changes to landscape, land use
- Emissions into the atmosphere, surface and subsurface waters
- Land subsidence, increased seismic activity and
- Solid wastes

The environmental effects of developing geothermal energy have still to be investigated in full, and a careful choice of power cycle and geothermal field has to be made. It is now generally acknowledged that geothermal fields have to be carefully monitored for several years prior to development in order to ensure the most viable field in environmental terms, as well as sustainable energy production. The assessment of the overall environmental impact consists of a local environmental impact assessment for the construction and operation of the plant and the distribution network and a life-cycle analysis.

3.4. The *Economic* model

Geothermal applications are characterized by a high initial cost and relatively low operation and maintenance costs. It is estimated that about 50% of total costs are due to the production and re-injection of the geothermal fluid, 40% are due to the plant construction, and the remaining 10% is due to other expenses (Kanoglu, Cengel, 1999). In practice one of the most important factors affecting the economic prosperity of the direct use of geothermal energy is the distance between the resource location and the service area. Thus, it is advisable that the direct use of geothermal energy should occur near the resource location. Most existing systems are characterized by transportation distances of less than 1 mile (Lienau, Lunis, 1991; ASHRAE, 1995). Furthermore, the successful implementation of a district energy delivery system requires that a significant share of the population of a community agrees not only to adopt it but also to pay for the construction of the delivery system. It must be mentioned that geothermal exploitation may be a significant financial risk operation with high levels of capital investment for exploration, drilling wells and construction - commissioning of the plant. Last but not least the cost of land necessary for the actual plant and the distribution network must be incorporated in the overall investment cost.

3.5. The *Decision Analysis* model

There exists a large number of decision variables in the design of a geothermal scheme, and the interactions among them are pervasive throughout the whole system. Each decision variable has several implications, and therefore the various attributes/criteria must be analyzed comprehensively. The aim of the decision analysis process is to provide a structured way to consider decisions and develop and support subjective judgements that are critical for good decisions.

In this sense, Multi-Criteria Decision Analysis (MCDA) methods are preferred to perform an integrated evaluation of projects in which there emerge considerable environmental and social impacts. Most of these impacts are difficult to measure in monetary terms and are thus hard to cope with in conventional methods, like cost-benefit analysis. RES projects in general have considerable environmental and social impacts and thus MCDA methods are to be favoured (Polatidis et al, 2006). In this work a step by step approach is applied to analyse the evaluation process for renewable energy source projects. The process consists of number of steps as follows:

- Framing the problem
- Identification of the stakeholders
- Creation of alternative scenarios
- Establishment of the decision criteria
- Criteria evaluation and preference elicitation
- Selection of the multi-criteria technique
- Model application
- Stakeholders analysis of the results and feedback

Experience from past projects has proved that an overall energy management scheme to serve community needs must combine narrative planning concepts such as new design, complete communities, green cities, with novel energy management models like energy cascading, demand-side management and integrated resource planning leading to an overall sustainable design pattern (Jaccard et al, 1997). At the same time it addresses environmental and social impacts for a required standard of living and infrastructure level. Community energy management, in particular, encompasses land use planning, site design, transportation management and local energy supply and delivery planning.

Also, it must be emphasised that community acceptance of local utilized geothermal is an intangible difficult to measure and forecast. It requires high participation rates and proper education for the citizens involved that must be aware of the benefits of renewable resources in view of their local and planetary benefits.

For this end, community support is the primary determinant in the success or failure of many geothermal district heating systems. The lack of a leading agency or champion promoting its development may be a hindering factor for the success of such a system. It is advisable that a geothermal energy centre is established in the local community which will be assigned particular priorities regarding routine operation, future extension of the system, and will assume the overall responsibility for the operation and maintenance. It should be also mentioned that periodic energy conservation campaigns and measures should be part of the normal operation of the system. Among the responsibilities of the geothermal energy centre will be the pricing model which will be justified on an economic, environmental and social basis.

All the above must lead to the direct engagement of the people involved and affected by a geothermal energy system. This commitment at the municipality level depends, among others, on the political, economic and local social circumstances (Nilsson, Martensoon, 2003). It is attained only if the activities related to the project do not result in drastic changes of the normal conditions of the area, and if the affected sectors can see some advantages in adjusting their lifestyle, and in modifying some practices to attain the new benefits arising from the project.

5. The Case-study at Lesvos - Greece

This case-study concerns the further exploitation of the geothermal field of Polychnitos-Lesvos. It is considered as a good opportunity for the application of a Sustainable Design framework in geothermal energy planning due to:

- its technical characteristics
- its proximity to the settlement of Polychnitos,
- the fact that it is currently under exploitation and finally,
- the increased interest of the local community for further exploitation.

Polychnitos is located 42 km southwest of Mytilene (capital of the island of Lesvos) in the east of Kalloni bay, which is protected under the Natura 2000 Network (Figure 4).

Fig. 4. Map of Lesvos island

It is characterised as a plain, semi-urban area. The total permanent population of the municipal department of Polychnitos is 2,975. The geothermal field is located near that settlement. Benefits and impacts will be accrued to this municipality. In Polychnitos there are totally 2,345 building of which 1,759 are residences, and only 264 of them have central heating systems, (boilers and air-conditioning systems). Cultivation activities and fallow land occupies more than 50% of the total land use in the area as it is shown in Table 1.

Table 1. Land use and total area of Polychnitos

Land use	Cultivation and fallow land	Municipality or communes	Private	Forests	Areas covered by water	Buildings and roads	Other	Total area
Area (10^6 m^2)	36.4	0.1	19.3	0.2	0.2	4.4	0.1	60.7

Precipitation in the area is rather low. Irrigation and water supply needs are covered by local springs and drillings located near the municipal departments. In the greater region of Polychnitos there are areas of high ecological significance and they are protected under the Natura 2000 Network. Part of Polychnitos area is located within the Natura 2000 Peripheral Zone C (PZ C), but renewable energy activities are promoted in this zone for the protection, management and further development of the Kalloni bay.

In the municipal department of Polychnitos there is a medium/low-enthalpy geothermal field with fluid temperature between 70 and 90^{o}C. It is the only geothermal field currently exploited in the island for greenhouse heating. There are five active drillings but only one of them has been fully used. Table 2 presents the energy characteristic of the geothermal field.

Table 2. Energy characteristics of the Polychnitos geothermal field

Total drillings [No]	Total permitted flow for usage [m^3/h]	Total flow in use [kgr/sec]	Temperature difference [^oC]	Installed capacity [MW]
5	185	51.4	45	9.67

At present the geothermal field is used for the heating of 40,000 m^2 of greenhouses. The system operates about 1700 hours per year. A total of 12 people are employed. The majority of the fluids are disposed in a nearby small brook and only a small part of them is reinjected back in the drill. The technical characteristic of the geothermal field are presented in Table 3.

Table 3. Technical characteristics of the Polychnitos geothermal field

Field area [Km^2]	Reservoir depth [m]	Temperature [^oC]	Average temperature [^oC]	Proven yield [m^3/h]	Probable yield [m^3/h]	Salinity (TDS) [gr/l]
10	50-150	70-90	85	300	1000	10

To achieve optimum exploitation of the Polychnitos geothermal potential, several combinations of the possible uses have to be formed and evaluated during the initial phase of the framing of the problem. Potential applications include development of alternative touristic activities (extension and renovation of the spas), agricultural activities (heating of greenhouses), and district heating.

Table 4 presents a possible decision matrix layout for RES projects with different levels of scenarios-alternatives according to the initial investment.

Table 4. Renewable energy decision analysis; layout of a multi-criteria procedure

Alternative scenarios (level of investment)	**C R I T E R I A**			
	Resource (e.g. Fuel saved)	Economic	Social (e.g. no of jobs)	Environmental
Small	x	x	x	xxxx
Medium	xx	xxx	xx	xx
Large	xxx	xxxx	xxx	x

Note: No of x's indicates possible benefits for the scenario involved

The evaluation criteria incorporate the basic axes of sustainable development, i.e. resources, economy, environment, energy, technology, society.

Finally, a variety of MCDA techniques exist and the analyst could choose the one that best matches with the particular features of the problem at hand (Polatidis et al, 2006).

4. Discussion - Conclusions

The geophysical, resource-based, technological, economic, environmental and social characteristics of the different components of geothermal district energy systems, as well as the plentiful interactions which take place among them, are discussed, and a new design framework is presented to determine the sustainability dimensions included. Particular emphasis is devoted to the interface between the local character of these systems and the specific structure of the semi-urban areas they are designed to serve.

This framework for the sustainable design and development of geothermal systems proposes an integrated planning process and identifies essential operational characteristics to underline the 'intangible' character of these systems, and, hence, the need for a comprehensive approach to their planning and management.

The developed methodology was used to study the feasibility of direct exploitation of a geothermal heating system in Polychnitos, Lesvos island, Greece. The area is characterized as semi-urban with moderate thermal load densities. Nevertheless, the methodology developed here can be applied to other areas with similar geothermal resources and characteristics. Results should indicate whether the service town is large enough, dense enough, and in close proximity to the resource for profitable development.

Future production schemes are likely to be based on considerations of sustainability, environmental protection and careful resource management, adopting low production rates that can be sustained over long periods of time. Fluid re-injection is an increasingly popular option of environmental management as well as cascaded use.

The model developed in this work enables planners to estimate energy-depended economic activities for a particular location. It can assist with regional policy for sustainable development and at the same time it allows the determination of the necessary infrastructure and the transport and communication activities needed. It may be used in rural, semi-urban and urban areas and it particularly employs land use analysis and decision analysis.

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